USING NERVE SIGNALS FROM MUSCLE AFFERENT ELECTRODES TO CONTROL FES-BASED ANKLE MOTION IN A RABBIT

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Abstract- **Electroneurographic (ENG) signals were extracted from muscle afferent fibers and used for real-time closed-loop control of FES-based ankle movements in a rabbit preparation. For extraction of the ENG signals, tripolar cuff electrodes were implanted onto the peroneal and tibial nerves in the left hind limb. A neural network was used for extraction of joint angles from the recorded ENGs. For stimulation purposes, percutaneous stainless steel wires were placed intramuscularly into the tibialis anterior and lateral gastrocnemius muscles, respectively. Stimulation intensity was varied by changing the applied pulse width (PW). Step and sinusoidal tracking tasks were performed using a standard PID controller.**

Results showed that the system's performance is highly sensitive to the initial joint angle; best results were obtained when starting with the ankle joint at a neutral, rest angle. Further, angles estimated from the ENG (by the neural network) lost correlation with measured angles as a given experiment progressed. Improvements were seen when the neural network was allowed to learn intermittently during an experimental session. Finally, a standard PID controller required frequent retuning during an experimental session, which, not surprisingly, suggests that an adaptive controller should be used.

***Keywords* – Natural sensors, neural prosthesis, implanted electrodes, functional electrical stimulation, closed-loop control, artificial neural networks, nerve signals.**

I. INTRODUCTION

Persons with paralysis of upper and lower limbs require the use of reliable, robust, closed-loop, and often adaptive devices that would allow them to perform basic tasks by means of applied Functional neuromuscular Electrical Stimulation (FES). However, control of FES-based movements can be enhanced by proper estimation of the current state of motion. For example, in the case of a paralyzed subject walking with the aid of FES, it is crucial that we use reliable sensory information pertaining to the output angular trajectories. The latter information can be obtained from sensory nerve fibers stemming from musculotendinous tissue to the spinal cord (i.e., muscle afferent fibers). A number of features in both time and frequency domains can somehow convey the necessary information albeit in a non-linear and time-variant fashion, and with signal-to-noise ratios much less than unity for cuff electrodes. Thus, our research group has been using implanted cuff electrodes to extract relevant information by analyzing signals obtained directly from the nerve bundles that carry it [1, 2, 3]. So far, a simple approach has been taken: rectified and bin integrated (RBIN) Electroneurographic (ENG) signals have been monitored and have been found to allow for a reasonable mapping onto angular and torque data by means of neural and fuzzy models [1, 2]. The present paper shows our first findings from using the extracted angular information in a closed-loop controller.

II. METHODOLOGY

A. Experimental Setup

Acute experiments were conducted with 4 female New Zealand rabbits. The rabbits were pre-anesthetized with an injection of Midazolam (2.0 mg/kg; Dormicum™, Alpharma, Norway). Then, after 15 to 20 min, anesthesia was initiated by an injection of Hypnorm™ (0.095 mg/kg Fetanyl + 3.0 mg/kg Fluranison; Janssen Pharmaceutica, Belgium). The anesthesia was maintained by applying intramuscular injections of Dormicum™ (0.15 mg/kg Midazolam), and Hypnorm™ (0.03 mg/kg Fetanyl + 1.0 mg/kg Fluranison) every 20 min. All procedures were previously approved by the Danish Committee for the Ethical Use of Animals in Research. During the experiments the rabbits were placed onto a mechanical device for fixating the knee and ankle joints in place [3].

For extraction of the ENG signals, tripolar cuff electrodes were implanted onto the peroneal and tibial branches of the sciatic nerve in the left hind limb. To minimize cutaneous inputs, the sural nerve was transected distal to its origin in the tibial nerve. The tibial and peroneal nerves were also transected just above the ankle joint to minimize sensory inputs from the foot. The cuff electrodes' internal diameters were 2 mm for the tibial nerve and 1.8 mm for the peroneal nerve. The cuff length was 22 mm (10 mm between each contact zone) in both cases. The cuff electrodes were manufactured according to the procedures in [4] but with a longitudinal cut to open the cuff.

For stimulation purposes, percutaneous stainless steel wires were placed intramuscularly into the tibialis anterior and lateral gastrocnemius muscles, respectively, in the same hind limb as the cuff electrodes. A constant current stimulator was used with the output set to 5mA. Stimulation intensity was varied by the controller through changes in the applied pulse width (PW) (from 0 to 500 µs, in 10µs steps).

The ENG signals were sampled at 10kHz. When FES was applied, ENG was recorded only for 4ms before each stimulation pulse to eliminate stimulation artifacts [5]. A neural network (trained off-line) was used for extraction of joint angles from the ENGs. Inputs for the neural network were the mean ENG values over the above 4ms period.

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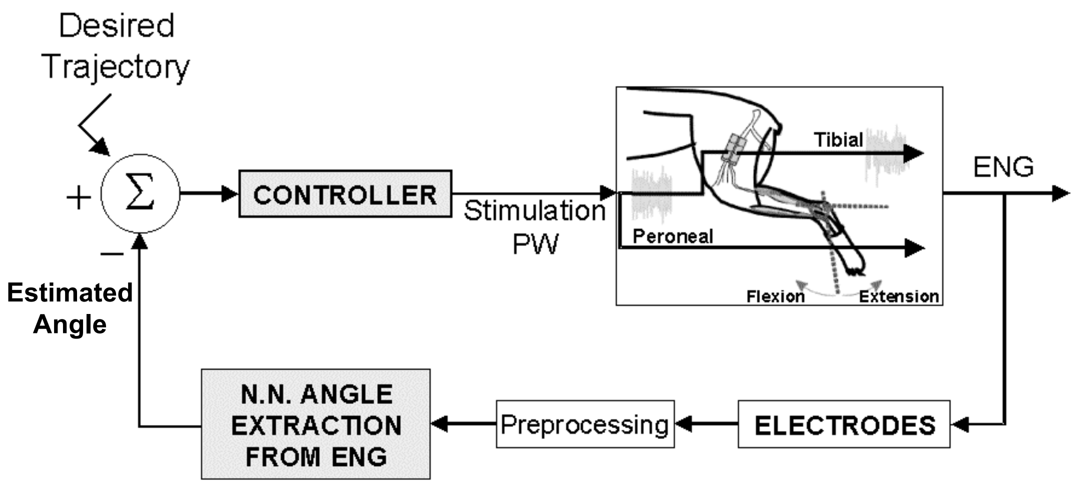


Fig.1 – Closed-loop control of FES-based rabbit ankle motion using feedback from muscle afferent fibers. The neural network for angle extraction had 4 input neurons (1 RBIN tibial ENG channel, 1 RBIN peroneal ENG channel, plus one delay for each RBIN channel), 20 hidden layer neurons, and one output neuron whose output was proportional to the predicted angle. The neural network also had an Elman-type recursive connection for each hidden and output layer neuron.

B. Closed-Loop Control

FES intensity was varied by the controller through changes in the applied pulse width (PW). Step and sinusoidal tracking tasks were performed using a standard PID controller. An overview of the closed-lop system is shown in Fig. 1.

Further, an optical angle sensor was used to measure the real ankle joint angles as a function of time. The readings from the optical sensors were used for monitoring both the controllers performance and the adequacy of the angle predictions from the neural network.

III. RESULTS AND DISCUSSION

A. Controller Test

To verify the best possible control performance to be expected from the system shown in Fig. 1, we ran several tests with an optical angle sensor that bypassed the ENG and angle extraction routines. The use of ENG for extraction of the angles is expected to yield worse system performance due to the errors in angle predictions inherent in the neural network approach. Thus, direct, measured angular data were used as feedback for tuning the PID controller and for testing its best possible performance.

Tuning of the controller was done using the Ziegler-Nichols method. However, as a given controller test progressed, the controller’s performance was found to rapidly degrade due mainly to the time-variance of the muscles’ response to stimulation (Fig. 2). Thus, continuos retuning of the controller was required during all the experiments. However, the process of retuning required the application of FES to the muscles, which accelerated the onset of muscle fatigue. Thus, it is suggested that, in the future, an adaptive controller be used instead.

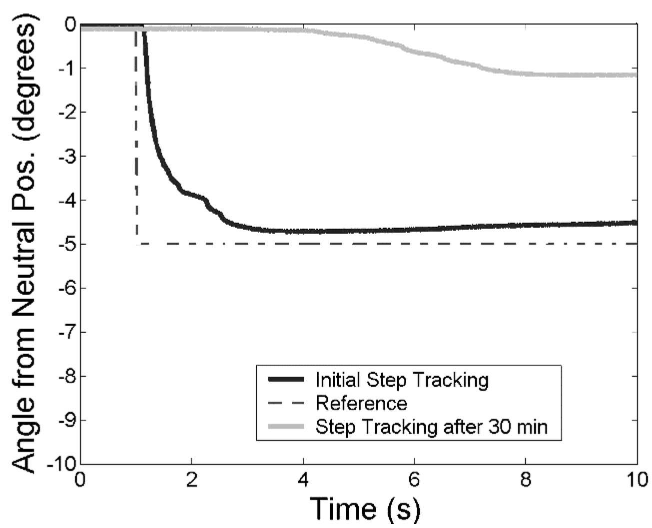
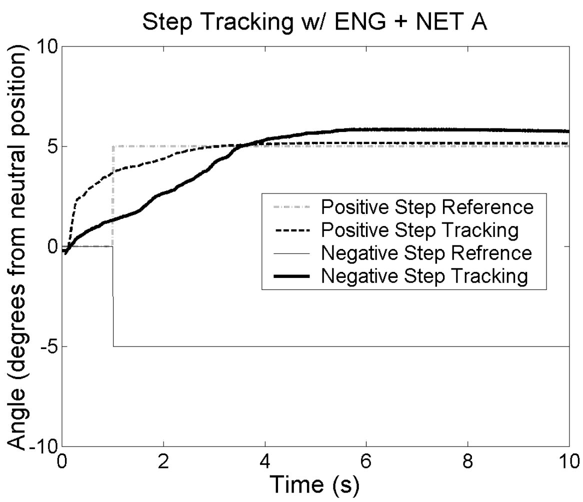


Fig. 2 – Decrease in system performance due to time-varying muscle output. A step tracking task is displayed. Notice how the system tracks the desired angle much better at the beginning of a test, as compared to after 30 min of intermittent FES. The data shown are for a single rabbit.

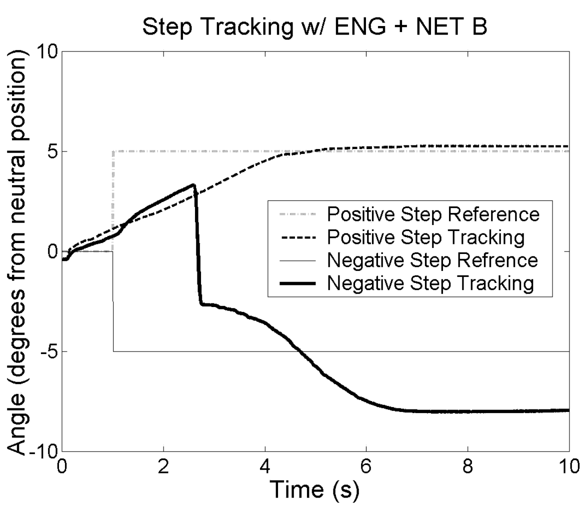
B. Closed-Loop with ENG

Preliminary results showed that the system's performance was highly sensitive to the initial joint angle. Best results were obtained when starting with the ankle joint at a neutral, rest angle. This value was to be between 100^o and 120^o for all rabbits.

Control was first performed with a neural network trained off-line only with data from rabbits used in previous experiments (see [1]). The performance of the closed-loop system was found to be very poor with this network, termed NET A. The poor performance was found to be mainly due to very noisy angle predictions from NET A based on the input ENG. Improvements were found when an 8-point moving average smoothing window was applied to the network's output (longer windows added little further improvement while adding unduly long processing times and delays). Further, angles estimated from the ENG by the neural network lost correlation with measured angles as a given experiment progressed. Improvements were seen when the neural network was allowed to learn intermittently during an experimental session (leading to NET B). In this case, the closed-loop process was stopped for 15 min, during which the neural network was allowed to learn based on data for the rabbit being used in the specific experiment. This neural network tuning process was found to yield substantial improvements, although the system's performance was still found to be far from acceptable (Fig. 2): long tracking delays and final offsets are still observed.



(a)



(b)

Fig. 3 – Improvement in control performance using ENG. (a) NET A: original neural network trained solely with data from previous experiments. (b) NET B: NET A submitted to output smoothing and rabbit-specific tuning. Data shown are for a single rabbit.

IV. Conclusions

Preliminary results showed that the system's performance was highly sensitive to the initial joint angle. Best results were obtained when starting with the ankle joint at a neutral, rest angle. Control with feedback from ENG and a neural network previously trained solely on data from other rabbits yielded poor performance. Improvements were seen when neural network outputs were smoothened and the network was allowed to learn intermittently during an experimental session. Finally, a standard PID controller required frequent retuning during an experimental session. Thus, it is suggested that neural network online-learning and an adaptive controller be used in the future.

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